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Modeling and testing of multi-resolution morphological gradient distance relay algorithm

A.A. Saad[a], M.F. El-Naggar[a], E.H. Shehab_Eldin[a] a*

[a]*Faculty of Engineering, Electrical Power and Machines Department, Helwan University, 1 Sherif, Helwan, Cairo, Egypt*

Abstract

This paper describes modeling and testing of a digital distance relay for transmission line protection using MATLAB/SIMULINK. ATP is used for detailed modeling of a power system network and fault simulation. SIMULINK is used to implement multi-resolution morphological gradient (MMG) relaying algorithm. MMG modeling is an interactive simulation environment for relaying algorithm design and evaluation. The basic principles of MMG relaying algorithm and some related algorithms such as tripping and fault location scheme are also described in this paper. Test results show that MMG relaying algorithm can detect and define fault location accurately within 1 milli-second.

Keywords: Mathematical morphology (MM); Power transmission line; Ultra-high-speed protection; ATP; MATLAB SIMULINK.

1. Introduction

Ultra-high-speed protection of the transmission line developed using mathematical morphology (MM). The technique is used to extract transient features from fault- generated voltage and current wave signals propagate along transmission-line [1].The MMG technique provides the excellent capability of extracting the transient features of fault waveforms as well as their polarities. Therefore, such sudden changes are successfully used to detect and to define the fault location [2]. In this paper, modeling and testing of MMG relaying algorithm will be presented. The evaluation of validity of MMG relaying algorithm, which helps in designing of this relay also discussed. The ATP [3] is used to simulate the power system and its electromagnetic transient phenomena.

* Corresponding author. Tel.: +02-0111-087-9448.
E-mail address: ahmed.saad09@yahoo.com.

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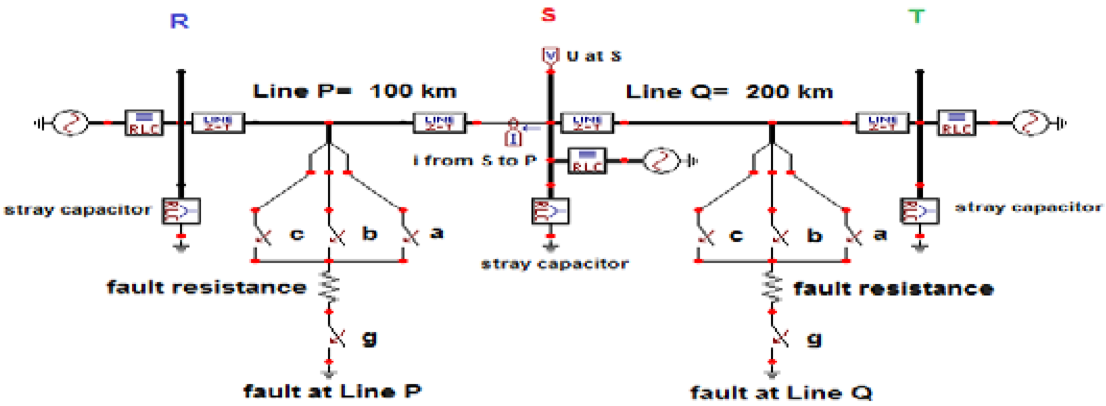


Fig. 1. ATP constructs the simulation systems diagram of 500 Kv system.

MATLAB/SIMULINK program [4] are becoming popular tool for engineering application, but it is less accurate than ATP programs specially in transmission line and power transformer modeling [5]. On the other hand, MATLAB/SIMULINK is considered the best choice in case of signal processing simulation. Therefore, MMG relaying algorithm will be simulated using MATLAB/SIMULINK blockset which helps in real time implementation of relying algorithm.

2. Power System Simulation

Simulation techniques have been successfully applied for the verification of the performance of newly developed protective relay systems. In this respect, simulation has proven to be a valuable complement to field testes, not only from points of the costs and the difficulties but also in performing full-scale tests in primary systems.

ATP and MATLAB are used as tools to simulate of electrical power system configuration. ATP is used in this paper because it is designed to simulate the physical processes of transmission lines and transformers, not only quickly and in convenient way than MATLAB/SIMULINK but also has high accuracy in case of electromagnetic transient nature in electric power system [5].

As shown in Fig 1., A 500 Kv power system is established. The simulation of each station source (R, S and T) can be replaced by the The'venin equivalent circuits. Three phase distributed transposed line model is used to simulate two lines (P = 100 Km and Q = 200 Km). Three phases star connected capacitors are used to simulate stray capacitors at each bus and power system parameters are shown in appendix A.

3. MMG Relaying Algorithm

MMG relaying algorithm is used in transmission-line protection based on a signal processing tool called mathematical morphology (MM) that used in image processing and machine vision. The algorithm of relay uses MATLAB/SIMULINK program the algorithm to build the algorithm as follows.

3.1. Multi-resolution morphological gradient

The basic morphological gradient (MG) is defined as the arithmetic difference between the dilation and the erosion by the elementary structuring element (SE) of the considered signal. Dilation and Erosion are two basic operations in MM and derived from the definitions of Minkowski's addition and subtraction [1,2]. Let F denote a signal and g denote a SE, and the length of g be considerably shorter than that of F. Dilation and Erosion defined as follows,

$$(F \oplus g)(x) = \delta_g(x) = Max\{F(x+s)+g(s) \mid (x+s) \in D_F, s \in D_g\} \quad (1)$$

$$(F \ominus g)(x) = \varepsilon_g(x) = Min\{F(x+s)-g(s) \mid (x+s) \in D_F, s \in D_g\} \quad (2)$$

Where $\oplus$ and $\ominus$ is dilation and erosion operator respectively, D_F and D_g are the definition domain of F and g respectively, x is the sample of signal F. Therefore, MG is denoted by ρ_g.

$$\rho_g = \delta_g(x) - \varepsilon_g(x) \quad (3)$$

In order to detect the sudden changes on the transient wave, a multi-resolution morphological gradient (MMG) [2] is introduced to depress the steady-state components and enhance the transient ones. Based on the definition of MG and SE, the dyadic MMG with level a is defined as,

$$[\rho_{g+}]^a = \delta_{g+}([\rho]^{a-1}) - \varepsilon_{g+}([\rho]^{a-1}) \quad (4)$$

$$[\rho_{g-}]^a = \varepsilon_{g-}([\rho]^{a-1}) - \delta_{g-}([\rho]^{a-1}) \quad (5)$$

$$[\rho_g]^a = [\rho_{g+}]^{a-1} - [\rho_{g-}]^{a-1} \quad (6)$$

When $a=1$, $[\rho]^0=F(x)$, $[\rho_{g+}]^a > 0$ and $[\rho_{g-}]^a < 0$, which corresponds to the ascending and descending edges of the waveform. Thus, ρ^a is able to detect not only the location of waveform changes but also their polarities. In addition, the higher the level is processed, the more details about the changes are revealed.

Fig 2. Shows MATLAB/SIMULINK block diagram that used to make modeling for detailed two levels MMG, when level one use eight samples structuring element with zero values. After finding dilation and erosion for each positive and negative edges, the model will apply equations (4-6) to find level number one of multi-resolution morphological gradient and level two will be found by the same method as shown in Fig 2. On the other hand, four samples only used to give higher frequncy component.

By applying a signal $F(x)$ on MATLAB/SIMULINK block diagram algorithm, detailed output results is shown in Fig 3-a. for level one and in Fig 3-b. for level two. The two levels are made to give more accurate details of changes in signal $F(x)$. So, MMG algorithm succeeded not only for detecting transients in a signal but also gave its polarities.

3.2. Fault detection

When a fault occurs, traveling wave fronts appear on the line, and those will propagate along the line and reflect at a discontinuity points [6]. For a single transmission line, the MMG algorithm detects traveling wave and compare its value with a certain threshold to discriminate between the healthy and faulty conditions.

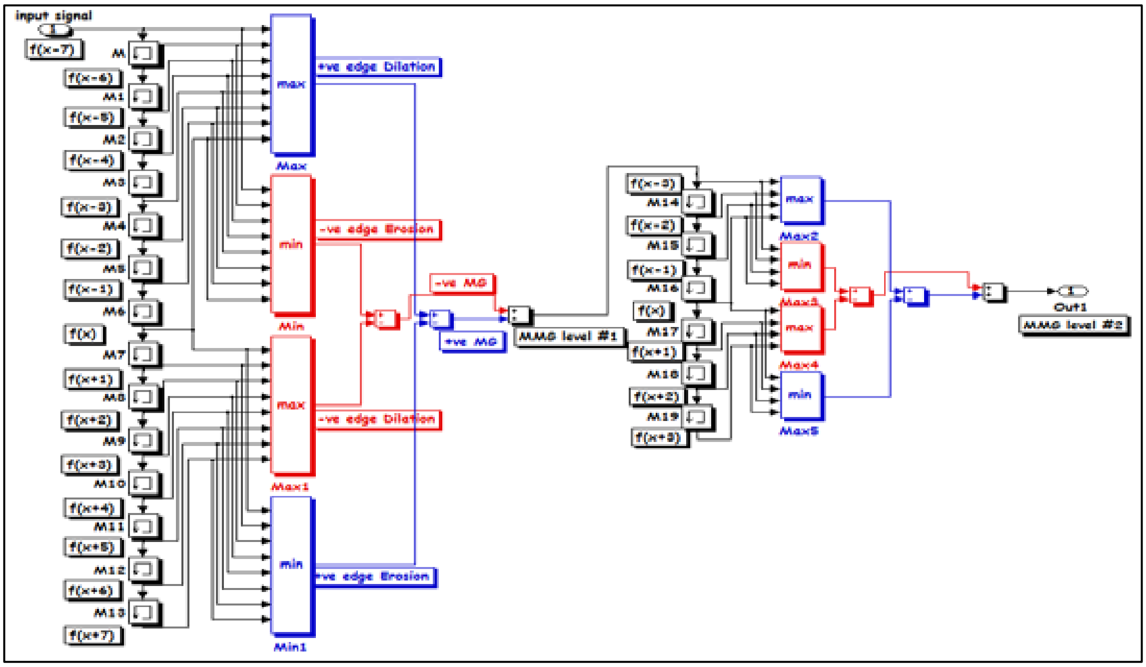
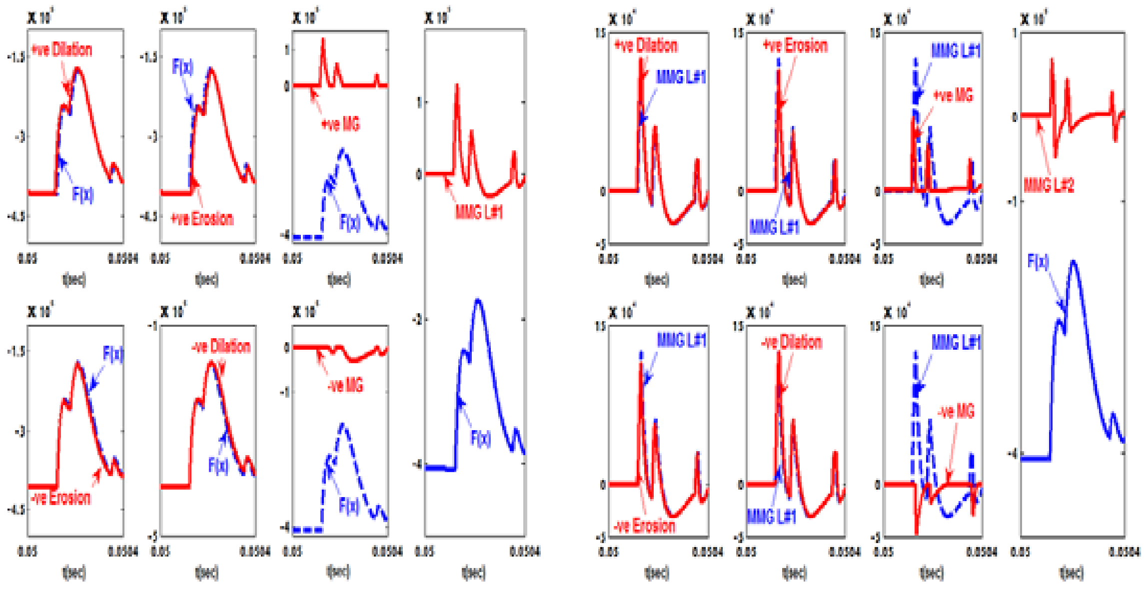


Fig. 2. MATLAB/SIMULINK block diagram for MMG algorithm.



(a) (b)

Fig. 3. MMG detialed results. (a) level one; (b) level two

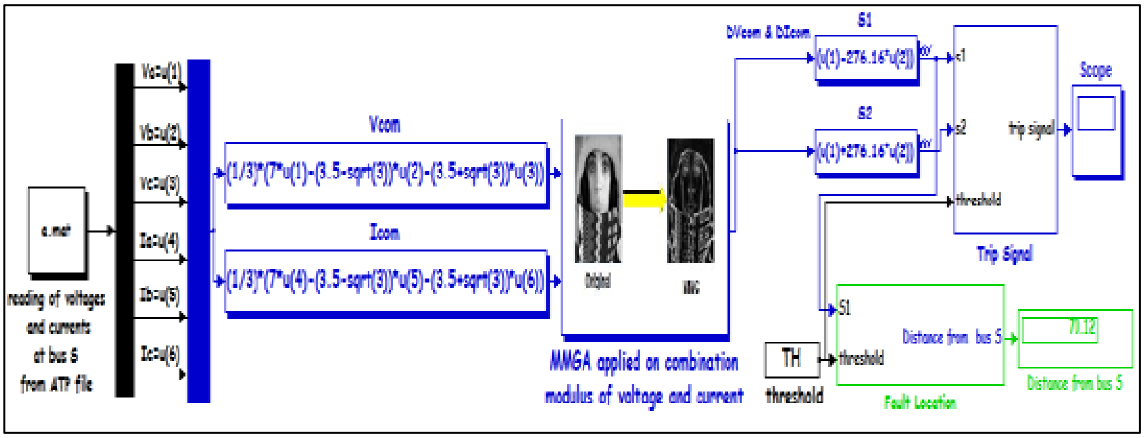


Fig. 4. MATLAB/SIMULINK block diagram MMG relaying fault detection algorithm at bus S.

With extension to three-phase transmission system, the phase variations of currents and voltages are decomposed into modal components using the Clarke transformation. The Clarke modal components for current or voltage transformation are,

$$\begin{bmatrix} F_0 \\ F_\alpha \\ F_\beta \end{bmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{pmatrix}\begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix} \tag{7}$$

The aerial mode components such as F_α or F_β component is used in the previous researches on traveling wave protection[7]. Either F_α component or F_β, component may be failed to detect some kinds of fault because their modal value is equal to zero in cases of B to C fault and A to ground fault [6]. So, combination modulus will be used to solve Clarke modal problem. The definition of Combination Modulus F_{com} is given by,

$$F_{com} = K_{com}\, F_\alpha + F_\beta \tag{8}$$

Where $K_{com}=3.5$ is the combinatorial coefficient. It is concluded that all kinds of fault can be detected by using the combination modulus [6]. The Combination Modulus F_{com} is given by,

$$F_{com} = (1/3)\ [\ 7F_a - (3.5 - \sqrt{3})\ F_b - (3.5+\sqrt{3})\ F_c] \tag{9}$$

A directional protection relay is situated at the end of section *P* near busbar *S*. The forward direction is defined at the relaying point as current flowing from busbar *S* into the protected section *P*. The relaying signals adopted in this scheme, initially introduced in [7] and [8], are given as,

$$S_1 = DV_{com}\,(t) - R_0\, DI_{com}\,(t) \tag{10}$$

$$S_2 = DV_{com}\,(t) + R_0\, DI_{com}\,(t) \tag{11}$$

Table 1. Detection criteria

Case	$\lvert S_1 \rvert$	$\lvert S_2 \rvert$
Forward fault	>TH	>TH
Backward fault	<TH	>TH
Healthy	<TH	<TH

Where R_0=*276.16* Ω is a surge replica resistance and its value is arranged as to match 500 kv line surge impedance Z_0 closely. DV_{com} and DI_{com} are a combination modulus of MMG transient signals of three-phase voltages and currents, respectively observed at the relaying point S are generated by the fault.
The overall algorithm for MMG relay is shown in Fig 4. Firstly, three phase voltages and currents are read from ATP file through MATLAB workspace to SIMULINK reading block. Then, each signal is decomposed by using combination modulus and result is applied to MMGA algorithm. Finally, relaying signals S_1 and S_2 are calculated. Discrimination between forward, reverse and healthy states can be made according to Table 1 [2]. Where TH is a threshold that will be selected according to sensitivity and selectivity of MMG relay. Theoretically, the value of threshold is zero but due to make relay do not work with power swing, load switching, transmission line energizing or external fault, it will be selected greater than zero.

3.3. Fault location calculation

The operating principle of single end (type A) fault locator is developed on the Successive identification of the high frequency transients arriving at the measurement point. Reference to the first and subsequently captured transients, including their polarities, allows the distance to the fault from each end of the line, as shown in Fig 5., to be calculated from the following formulae [2],

$$L_s = L-(T_2-T_1)c/2 \tag{12}$$

or $$L_s = (T_2 -T_1)c/2 \tag{13}$$

Where L_S indicates the measured distance between the fault and busbars S; T_1 and T_2 are the times when the captured transient Sequences are observed; C is the propagation speed on the transmission line; and L is the full length of the transmission line. When a fault occurs on the first half of the transmission line.The determination of the fault location depends on the polarities of the first and second wavefronts, i.e. when product of two polrities is positive, fault location is in the first line half and equation (12) will be applied. On the other hand, when product of two polrities is negative, fault location is in the second line half, and equation (13) will be applied.

4. Testing

Based on the discussion made in the previous sections, we can test the model of MMG relaying algorithm to detect fault. *C-G* fault will be made at line section *P*, at zero inception angle *(55 ms), 500* ohms arc fault resistance and at *70 Km* from bus *S*. To detect and catch accurate travelling wave transients on transmission line that has speed about light speed [1], *1MHZ* sampling rate is recommended for this model.

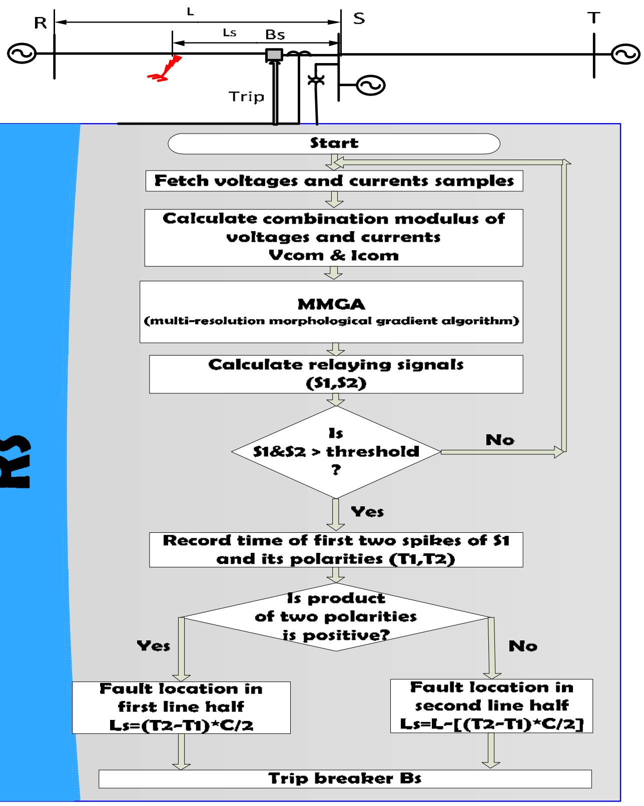


Fig. 5. Fault location algorithm flowchart.

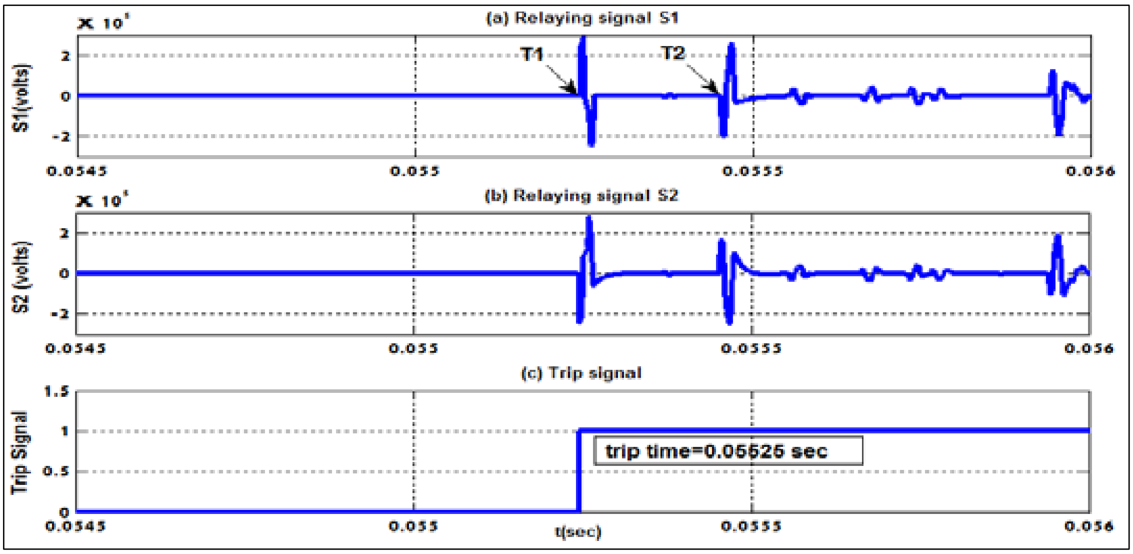


Fig. 6. (a) relaying signal S1; (b) relaying signal S2; (c) trip signal

Table 2. Various fault cases

Fault direction	Fault location (Km)	Fault type	RF (Ω)	□F (deg)	$\lvert S_1 \rvert$ (Kv)	$\lvert S_2 \rvert$ (Kv)	Trip signal	LS (Km)	Error (%)
Forward	1	a-g	50	0	114.6	96.4	1	2.87	1.87
	10	a-b	0	30	719.7	712.6	1	9.91	0.09
	25	b-c	40	60	309.3	308.3	1	25	0
	40	c-a	10	90	2497	2412	1	39.93	0.07
	50	a-g	50	0	75.5	78.8	1	50.01	0.01
	60	a-b-g	75	0	287.2	286.7	1	59.92	0.08
	75	a-g	50	30	704	710.4	1	75	0
	90	a-b-c	100	90	1826	1748	1	90.09	0.09
	99	a-g	50	0	36.6	35.15	1	97.13	1.87
Reverse	1	a-g	0	0	1.7	557	0	Fault location algorithm not activated	
	100	a-g	0	0	1.7	503.7	0		
	199	a-g	0	0	1.2	479.2	0		

For previous described case study, Values of Relaying signals S_1 and S_2 will exceed threshold value as shown in Fig. 6-a, b. Trip signal will appear after *0.25 ms* from fault occurrence as shown in Fig.6-c. In this case study, the difference between T_2 and T_1 will be measured *0.208 ms* and its product of first two spikes polarities will be negative. So, the measured distance equal to *70.12 Km* by *120 meters* error. Various fault cases at different fault inception angles *(□$_F$),* fault locations, fault resistances *(R_F)* and types are tested and described in Table 2.

5. Conclusion

This paper describes an automated protective MMG relay test system based on MATLAB/SIMULINK and ATP. The system combines ATP in power network modeling and SIMULINK in MMG relaying algorithm. It is clear that, the proposed model of MMG relaying algorithm succeeded under various fault conditions. It can detect faults, discriminate between forward and reverse faults and define the fault location accurately. The proposed algorithm model has been developed for real time implementation and can be coded into existing digital relay hardware.

Appendix A. 500 Kv transmission line simulated parameters

The power system parameter of simulated network is 500 Kv, 50 Hz and line constants are $R_0 = 0.247\Omega/Km$, $L_0 = 0.91\ \Omega/Km$, $C_0 = 2.94\mu\Omega^{-1}/Km$, $R_1 = 0.0217\Omega/Km$, $L_1 = 0.302\ \Omega/Km$, $C_1 = 3.96\mu\Omega^{-1}/Km$ propagation speed = $C = 2.873e5Km/Sec$. and stray capacitor at the *500Kv* bus is $31.416\ \mu\Omega^{-1}$.

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A. A. Saad was born in Cairo, Egypt, on September 30, 1985. He received the B.Sc degree in electrical engineering from Helwan University, Cairo, in 2007. Now he is studying for M.Sc in the Electrical Power and Machines Engineering, Faculty of Engineering, Helwan University, Cairo, Egypt. His research interests include digital relaying and application of intelligent methods to power systems.

M. F. El-Naggar was born in Helwan, Egypt, on September 1, 1972. He received the B.Sc and Msc degrees in electrical engineering from Helwan University, Cairo, in 1995 and 2002 respectively. He received the PhD from Helwan University, Egypt 2009. Now he is teacher of power system protection, Power and Machines Engineering Dept., Faculty of Engineering, Helwan University, Cairo, Egypt. His research interests include power system relaying.

E. H. Shehab_Eldin was born in Domiatta, Egypt, on September 17, 1952. He received the B.Sc and Msc degrees in electrical engineering from Helwan University, Cairo, in 1976 and 1982 respectively. He received the PhD from Cambridge University, England 1988. Now he is professor of power system protection, Power and Machines Engineering Dept., Faculty of Engineering, Helwan University, Cairo, Egypt. His research interests include power system relaying.